Technological Forecasting & Social Change 206 (2024) 123559

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Multi-index analysis with readiness levels for decision support in product design

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A R T I C L E I N F O

Keywords:
New product development
NPD
Readiness
Level

A B S T R A C T

The Technology Readiness Level (TRL) was introduced by NASA in 1974 to measure the technical maturity of equipment deployment in space missions. It has since been widely adopted for the assessment of technical readiness in novel products and systems across many sectors. But TRL does not capture all the dimensions needed to assess the maturity and suitability for production of a given product concept. Additional metrics have been proposed to measure other design parameters, but we note the lack of a comprehensive mechanism capable of assessing together *all* the parameters that affect the potential for success or failure of a product. In this article we propose the novel Multi-Index Analysis (MIA) methodology that maps existing metrics onto one comprehensive single index. In this work we demonstrate the application of MIA with 10 known metrics comprising 39 design dimensions to demonstrate that this approach enables a multi-factor analysis that is not possible with individual metrics. We detail four general cases for the application of this index including the single evaluation of one or more product design concepts, and the multiple evaluations of one or more product concepts made over time. Multiple evaluations yield trend data and this can aid in predicting the likely success of a product concept over its lifecycle. Modelling and predicting the evolution of MIA scores for different product concepts at an early stage of design enables an optimum solution to be selected and crafted. We provide a software tool to enable convenient MIA assessment.

1. Introduction

Within product design, emphasis is placed on Gestalt theory where an overall, holistic, perception of a product is of greater importance than the sum of its atomised, individual parts. Pioneering work by Pugh in 1991 (Pugh, 1991) suggested that product engineering and product success is improved when the design process is total, that is to say, any factor that may affect the successful development of a product should be considered during its development. Work in the field of simultaneous engineering has found that problems within New Product Development (NPD) arise where different elements are designed independently and without proper integration (Minguela-Rata, 2011). Concurrency has been shown to benefit NPD by the use of multidisciplinary teams with which to design the product simultaneously from multiple perspectives. This approach is advocated by many in the literature (Koufteros et al., 2001; Hauptman, 1996; Millson and Wilemon, 2002; Edmondson and Nembhard, 2009). Conversely, readiness level estimation is typically performed by assessing the product against a single specific metric on an ordinal scale to carry out a partial analysis from the point of view of a particular stakeholder. For example, technical merit may be assessed to index the *functionality* of a product; commercial prospects are measured to assess the product's *economic* viability; or readiness for *standardisation* may be applied — but these are only applied in isolation (ITU-T, 2021). NPD approaches and the work of researchers such as Pugh have, as identified, been applied in isolation; the various readiness and development levels reviewed in Section 2 have been developed as stand alone tools. This has resulted in a research need to develop an approach to combine and analyse these tools together. As such, the research objective of this paper is the MIA which may be used to concurrently analyse the quality of an NPD.

Our paper identifies a crucial gap in the existing methodologies for assessing product readiness. Traditional approaches, like the Technology Readiness Level (TRL), are limited in scope and do not capture all dimensions necessary to assess the viability of a product concept comprehensively. We argue for a more holistic approach that considers multiple factors affecting a product's success in the market. Our primary objective is the proposal and demonstration of a new methodology called Multi Index Analysis (MIA). This methodology aims to combine existing metrics into a comprehensive single index, allowing for a multifactor analysis that surpasses the capabilities of individual

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https://doi.org/10.1016/j.techfore.2024.123559
Received 5 January 2023; Received in revised form 18 June 2024; Accepted 23 June 2024
Available online 17 July 2024

metrics. The goal is to optimise product success by ensuring that all aspects of product design are considered and aligned. Our main research questions are (1) How can product success be maximised by optimising overall readiness rather than focusing on individual aspects of design? (2) What are the challenges in constructing a single MIA metric, and how can they be resolved? (3) How can MIA provide differential assessment in situations where multiple design approaches are considered? Our research contributes significantly to the field by proposing a more comprehensive and objective approach to product design assessment, and by addressing the limitations of existing methodologies.

We note that readiness levels are actively being discussed and developed and a noteworthy example from the engineering literature (Jones, 2024) proposes a methodology to improve accurate assessment of technology readiness for real-world applications. We also note that a related approach has been reported in Vik et al. (2021a) which focuses on new agricultural technologies. A dual readiness level approach was taken in Islam et al. (2020) to assess technology in addressing world challenges with the Internet of Things. The importance of readiness level frameworks, especially in the timely setting of technical and policy objectives, can be found in Kobos et al. (2018). Another recent example of an 'Aggregated Readiness Level' in the application area of Asphalt concrete, combines technology performance, market opportunity, regulatory environment, stakeholder acceptance, and organisation's maturity (Bontă et al., 2024). Our approach extends such works by being domain ambivalent, looking at many selected dimensions/levels, adding normalisation adjustments between dimensions/levels, by being quantitative and extensible in nature, and by being able to incorporate all the above approaches.

Expanding on Pugh's approach and drawing on selected methods in the readiness level literature, we present a methodology that allows for both a detailed and synoptic design assessment based on a set of indices chosen for its relevance to the design under consideration. In this work we have chosen what we consider to be the 10 most significant existing readiness indices in order to demonstrate the capabilities of the technique as comprehensively as possible. This axiomatic design contribution enables product evaluation to be expressed as a single Multi-Index Analysis (MIA) metric onto which may be mapped the individual index scores. In this work we demonstrate the usefulness of a multi-linear map, but alternatives such as multiplicative, harmonic, weighted or others may also be applied using the same methodology (Table 2).

This paper is organised as follows: We begin by discussing the limitations of the Technology Readiness Level (TRL). We then introduce Multi Index Analysis (MIA), combining existing metrics into a comprehensive single index. This approach enables multifactor analysis beyond the capabilities of individual metrics. We demonstrate its use with 10 known metrics comprising 39 design dimensions. We next emphasise the importance of a holistic view of a product rather than focusing on individual parts as considering all factors affecting product development leads to better product engineering and success. Next, we highlight issues arising from designing different elements independently without proper integration and advocate for a multidisciplinary, concurrent approach to product design.

We then present a discussion of how specific metrics are selected for partial analysis from the perspective of different stakeholders (e.g., technical merit, commercial prospects, readiness for standardisation). This is followed by our proposal of a methodology for both detailed and synoptic assessment, allowing for the combination of pertinent readiness levels into a multi-index readiness estimator. This includes, as an example, a selection of ten existing indices, each with descriptive milestones. The methodology we purpose can be broken into the following three components: (a) categorise existing readiness levels as sub-metrics and their constituent scales as design dimensions. (b) align sub-metrics so that a product reaches notionally equivalent milestones on each simultaneously. (c) as a product's success will be limited by its lowest score on any applied sub-metric, we propose that a product should be assessed using individual sub-metrics. These may then be combined to produce a score on a single index (MIA) measuring overall readiness. This methodology allows for objective design analysis in both quantitative and qualitative terms and provides a strategy to optimise product success.

Our theoretical contribution is (a) The introduction of a comprehensive concept of readiness that applies to the entire product, challenging the traditional approach of focusing on individual sub-metrics. This holistic view is crucial for understanding the overall readiness of a product for the market. (b) an expansion of Pugh's approach and recent methods in the readiness index literature, presenting a methodology that allows for both detailed and synoptic assessments. This methodology in a contribution to axiomatic design that enables the combination of various readiness levels into a single Multi-Index Analysis (MIA), allowing for a more comprehensive evaluation of product readiness. (c) MIA as a tool for objective design analysis, both in quantitative and qualitative terms which enables the mapping of individual index scores and the application of multi-linear (or other) mapping methods. The practical value includes (a) a methodology designed to optimise the overall success of a product. By achieving maximal readiness across all sub-metrics, a product is in an optimal condition to succeed in its intended market. (b) addressing the two principal challenges in constructing a single readiness level metric: the temporal independence of existing sub-metrics and the different index ranges. (c) a tool that provides valuable insights for decision-making in product development. It helps in understanding why a product design might be more successful in certain sub-metrics than others and guides designers in making informed choices during the design process.

2. An overview of selected readiness level literature

Various sub-metrics have been proposed to measure different aspects of readiness. The first to gain widespread use was the globally accepted Technology Readiness Level (TRL) (Rosen et al., 1989; Mankins, 1995; ISO, 2013). This sub-metric measures the technical competency of a technology. It has lead to work in related fields (Héder, 2017; Tomaschek et al., 2016) such as de jure standardisation (ISO, 2013) and has been applied as a research and innovation policy tool (EARTO, 2014; European Commission, 2020; Garg et al., 2017; Olechowski et al., 2015). The CRI (Commercial Readiness Index) was devised in 2014 (Australian Government, 2014) to measure aspects of financial viability. This measures the progress made for stakeholders with a commercial interest in a product's development. It has been recognised, especially in the grey literature (OSD, 2018) that problems can arise where design for manufacturability (DfM) has not been given sufficient consideration during the development of a product. The manufacturing readiness level (MRL) scale was devised to measure progress in manufacturability. A product's success is hampered if its constituent elements are not properly integrated with one another and cannot interoperate or if the product cannot interface properly with external elements. The systems readiness level (SRL) and an associated integration readiness level (IRL) have been proposed (Sauser et al., 2006; Austin and York, 2015) to measure systems integration. Frequently a product will require ongoing support of some kind once it has been received by the end user and without which it cannot be successfully deployed for its entire lifespan. The sustainment maturity level (SML) indexes this requirement (US, 2019). In recent work, other indices have been proposed to assess whether a market exists for the product (Demand Readiness Level — DRL) (Paun, 2011; Dent and Pettit, 2011); whether the regulatory environment is receptive to its introduction (Regulatory Readiness Level — RRL) (Kobos et al., 2018); whether a product is likely to be accepted by consumers (Acceptance Readiness Level — ARL) (Vik et al., 2021b); and whether the organisation proposing the product is ready to undertake its design and production (Organisational Readiness Level — ORL) (Vik et al., 2021b).

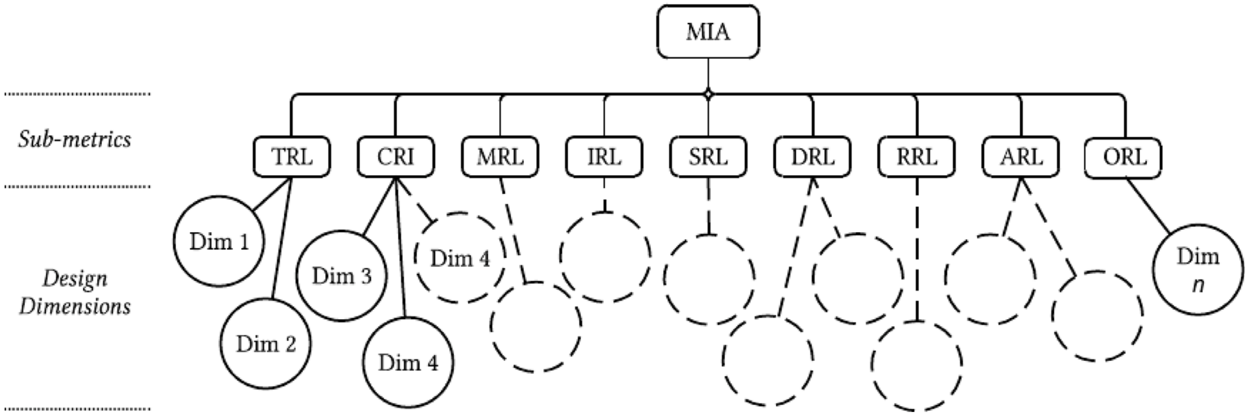

Fig. 1. Structure of MIA with sub-metrics and design dimensions.

To summarise, the use of readiness levels is an assessment against sub-metrics developed to as benchmarks for different dimensions of readiness in product development. The Technology Readiness Level (TRL) emerged as the first widely adopted metric, focusing on the technical competency of technology and influencing related fields such as standardisation and research policy. Numerous other readiness levels have been proposed which we will analyse to develop a comprehensive framework for evaluating a product's readiness across multiple critical dimensions.

3. Methodology

3.1. Design dimensions

While examining the existing readiness levels, we noticed that some are themselves comprised of multiple, more specific, scales. In this work we refer to the existing readiness levels as sub-metrics and to their constituent scales as design dimensions. The sub-metric/design dimension hierarchy, which can be generalised to all the included readiness levels, is shown in Fig. 1.

The sub-metrics have at least one design dimension. A list of the sub-metrics previously reviewed and their design dimensions is reproduced in Table 4.

3.2. Motivation

We propose that an essential feature of readiness as a concept as applied to any product is that it should apply *in toto*. The design strategy implied by a partial analysis by an individual sub-metric is focused on a product reaching the highest level on that single sub-metric irrespective of any other factor. A simple example easily shows this not to be an optimum strategy. Consider a product that has an impeccable technical performance (a high TRL score), but the design has evolved in such a way that it cannot be manufactured at the required scale (low MRL score). Despite its technical proficiency, this product cannot be successful since it is impossible to make it available in its intended market. Similar reasoning makes a similar case against other included readiness indices when these are applied in isolation.

What the sub-metrics allow, as individual indices, is for a product to be objectively assessed on individual criteria, but this does not provide a means to evaluate it *overall*.

Following this line of reasoning, we make the critical observation that *a product can only be as successful as its minimum score on any one of the sub-metrics that are applied during its appraisal*.

To improve on the current situation we propose that a product should be assessed using the individual sub-metrics, then these scores are taken together to produce a score on a single index that measures the readiness of the overall product or system. This latter index we call the Multi Index Analysis (MIA). The MIA score, as we have applied it with a linear map, is always limited by the lowest score on any sub-metric which in turn is limited by the lowest score on its constituent design dimension(s). The strategy of our novel approach is for the designer to maximise the product's MIA score by careful design choices that are informed by the potential impact of each decision across *all* sub-metrics. This MIA method provides for the following:

1. an objective design analysis is possible both in quantitative and qualitative terms.
2. a product that has achieved maximal readiness in all its sub-metrics is in an optimal condition to succeed in its intended market.
3. the implied product design goal becomes one of optimising *the product overall* rather than individual aspects of its design to maximise its overall readiness and therefore overall success.
4. design tradeoffs and design decisions are made during product development that are informed by their likely impact on overall readiness and therefore, product success. This becomes the guiding principle during product design.

The methodology that we propose allows for an objective design analysis both in quantitative and qualitative terms and provides a strategy to optimise the product success.

Two principal challenges emerged while constructing a single MIA metric: the existing sub-metrics are temporally independent of each other; and the indexes have different lengths (ranges). We discuss how these two problems were resolved next.

3.3. Determining the index alignments

The sub-metrics must be aligned so that a product reaches equivalent milestones on each sub-metric simultaneously. To achieve this we used various cues present in the individual sub-metrics' level wordings. For example, the MRL table for MRL 4 (OSD, 2018) states that this can only be aligned with TRL 4+, giving one of several indexing points between the two sub-metrics. The originating literature for other sub-metrics (e.g., MRL, CRI, DRL, ARL, RRL, ORL), specifically show tables indexing these sub-metrics to TRL, which is consistently chosen in the literature as a datum (OSD, 2018; Australian Government, 2014; Paun, 2011; Vik et al., 2021b). By a combination of these cues and with some judgements where cues were not explicitly present, we were then able to produce the alignment as shown in Table 1.

The alignments and number of levels for the varying sub-metrics dictated the $n = 15$ MIA levels to the index. The first 14 levels correspond to a unique combination of sub-metric scores. We added MIA 15 to represent a product that is retired from use for its intended original purpose, and to incorporate the concept of design for reuse,

Table 1
Sub-metric alignments. Each multi index analysis level defines a set of levels over the sub-metrics (technology readiness level, commercial readiness index, manufacturing readiness level, sustainment maturity level, integration readiness level, systems readiness level, demand readiness level, regulatory readiness level, acceptance readiness level, organisational readiness level). The MIA adjusted scores are described in Section 3.4.

Sub-metric	Multi Index Analysis (MIA)																
	1	2	3		4		5	6	7	8	9	10	11	12	13	14	15
TRL	1	2		3		4	5	6		7	8			9			
MIA_{TRL}	1	2		3		4	5	6		8	9			14			15
CRI						1						2	3	4	5	6	
MIA_{CRI}						8						10	11	12	13	14	15
MRL	1	2		3		4	5	6	7	8		9			10		
MIA_{MRL}	1	2		3		4	5	6	7	8		10			14		15
SML	1	2		3		4	5	6	7	8		9	10	11		12	
MIA_{SML}	1	2		3		4	5	6	7	8		10	11	12		14	15
IRL		0	1	2	3	4	5	6	7	8				9			
MIA_{IRL}		2	2	3	3	4	5	6	7	8				14			15
SRL		0	1	2	3	4	5	6	7	8				9			
MIA_{SRL}		2	2	3	3	4	5	6	7	8				14			15
DRL	1	2		3		4	5	6		7	8			9			
MIA_{DRL}	1	2		3		4	5	6		8	9			14			15
RRL	1	2		3		4	5	6		7	8			9			
MIA_{RRL}	1	2		3		4	5	6		8	9			14			15
ARL	1	2		3		4	5	6		7	8			9			
MIA_{ARL}	1	2		3		4	5	6		8	9			14			15
ORL	1	2		3		4	5	6		7	8			9			
MIA_{ORL}	1	2		3		4	5	6		8	9			14			15

repurpose or recycling which is omitted from any of the included sub-metrics.

Alignment solves the problem of time equivalence between sub-metrics but not the issue of different index ranges {1–9, 0–9, 1–12, 1–10, 1–6}. To facilitate an appropriate analysis, these ranges were normalised such that there was a numerical equivalence between the sub-metrics in the same MIA position.

3.4. Ranging of sub-metrics

To resolve the range problem, we created a table of 'MIA-adjusted' scores for each metric $\{MIA_{TRL}, MIA_{CRI}, \dots\}$. The adjusted scores were found, on a per sub-metric basis, from the alignments of the sub-metrics in Table 1 by inspection of the highest equivalent MIA score for each position. The MIA equivalent value was then inserted into a similar position as a new MIA-adjusted scale (italics in Table 1). For example the SRL = 0 position spans MIA 1 – 2 thus its adjusted score is $MIA_{SRL} = 2$.

With normalised sub-metric scaling, calculations can be performed on the values more conveniently (described later). Any future references to sub-metric scores should be taken as being MIA-adjusted scores, i.e., sub-metrics using the MIA 1 – 15 range and not the original and various index lengths.

3.5. Deduplication of sub-metric dimensions

Since the sub-metrics themselves comprise one or more design dimensions (Fig. 1 & Table 4) and the sub-metrics were devised independently of one another, there is the risk of duplication in the design dimensions. This is undesirable since the single parameters are being measured more than once and not always using exactly the same criteria. We also noticed that the TRL sub-metric actually contained two distinct design dimensions, despite this not being explicitly stated in the original literature, so these were separated before deduplication.

We employed the following three specific steps to remove the duplication:

1. To explore the extent of the duplication as comprehensively as possible, we constructed a comparison matrix (Fig. 10), derived from the design dimension titles, as designated in the literature (Rosen et al., 1989; Mankins, 1995; ISO, 2013; Australian Government, 2014; OSD, 2018; US, 2019; Sauser et al., 2006; Austin and York, 2015; Paun, 2011; Vik et al., 2021b) and listed in Table 4.
2. By inspection of these titles, we made pairwise comparisons between all the dimensions and then recorded any judged correlations in the matrix. For example, when comparing (3) and (37), the titles "regulatory environment" and "regulatory status", indicates some duplication. For convenient indexing, each design dimension was numbered in the matrix. We found that there were 10 possible duplicate incidents within the following set of design dimension pairs: {(2, 34), (3, 37), (9, 36), (1, 5), (4, 38), (6, 15), (6, 16), (8, 20), (8, 11), (1, 14)}. This sieve technique was useful in reducing the number of possible matches from $(39^2 - 39)/2$ to 10.
3. The remaining 10 possible matches were examined comprehensively by additionally comparing the design dimension descriptions at *each position in their range*. We resolved each duplication case and show this result below. The process led to some design dimensions being amalgamated and some being added or removed from sub-metrics as necessary. We use the notation $-x$ where a dimension should be removed from a sub-metric and $+y$ where one is added. Prime symbols on dimension numbers indicate where a dimension has been revised by amalgamation.

Of the 10 matches identified, changes were necessary in 5 cases:

$\{2, 34\}$ Resolution: amalgamate (2) into (34). TRL (−2), IRL (−34) (+34′).

$\{3, 37\}$ Resolution: amalgamate (3) into (37). CRI (−3), RRL (−37) (+37′).

$\{9, 36\}$ Resolution: amalgamate (9) into (36). CRI (−9), DRL (−36) (+36′).

$\{1, 14\}$ Resolution: amalgamate (14) into (1). MRL (−14), TRL (−1) (+1′).

$\{8, 20\}$ Resolution: amalgamate (8) into (20). MRL (−20) (+20′), CRI (−8) (+20′).

By this method we have achieved both a holistic multi-index analysis scale and sub-metrics that are comprehensive but with minimal duplication. Additionally, all elements in the scale are sourced from one set of unique and precise design dimensions.

The completed MIA system is contained within a large MIA matrix similar to that of Table 1 but with additional details of design dimensions and the verbose level descriptions. Because of space constraints we have included this in the supplementary material.[1] We have additionally produced a software tool with a graphical user interface that can be used to carry out the assessments and analyse the results. This also is available in the supplementary material.[2]

4. Application

We have chosen four case studies where the MIA scoring system has been applied in four general cases, to evaluate:

1. a single product with a single assessment (to understand the balance of the design, described later);
2. a single product with multiple assessments (to assess the impact of changes made during design iterations or as a project management tool to assess project maturity during product development);
3. multiple products with a single assessment (to compare product solutions to a given problem in e.g., technology selection or procurement), and;
4. multiple products multiple times (to compare how competing simultaneous solutions to a problem are developing over time).

The procedure in making the MIA assessment is as follows:

For each of the ten sub-metrics, the product's status is compared to the level definitions of that metric's design dimensions (as contained within the MIA matrix). When the product meets all the criteria over that sub-metric's design dimensions for a specific level, it is scored at that level on that sub-metric. where a range of levels are obtained for sub-metrics across multiple design dimensions, the sub-metric level is set by the lowest scoring (limiting) dimension in accordance with our reasoning presented in the methodology section.

For example, in assessing TRL which has only one design dimension ($1'$), a product is judged to have met the criteria "Technology concepts formulated" which is found in the matrix in position TRL 2. This then is the TRL component of its MIA score. Similarly, suppose CRI is being assessed which has six design dimensions $4, 5, 6, 7, 20', 10$. The product is judged in turn against all six dimensions. In dimensions 4, 5, 6, 7, 20 it is found to satisfy level CRI 11 but in dimensions 10 it satisfies only CRI 10. It is thus scored CRI 10 since this is the limiting dimension within that sub-metric.

4.1. Balanced design

Aside from the MIA single score, the difference between the highest scoring and lowest scoring sub-metric at points in a product's development gives valuable information. We call this difference the 'interval' and it is found at each assessment by applying a $min()$ and $max()$ function over the set of sub-metric scores and then calculating $max - min$. An example is given in Table 2, showing 4 sets of hypothetical MIA assessment scores and their associated interval values. The interval is of particular interest since this value must necessarily converge to 0 if all sub-metrics attain a score equivalent to MIA 14. *Minimising the interval thus directs the designer's core strategy*. We propose that where the interval is non-zero that the product's design is 'unbalanced' and where it is zero that the design is 'balanced'.

The principal value in the MIA approach is understanding the characteristics of an unbalanced design and applying this knowledge to improve the product during its development. We suggest that unbalance comes about where design choices have unduly favoured one sub-metric at the expense of another. With our approach, where the interval >0, the product designer is continually prompted to consider what choices about the design can be modified to reduce this interval magnitude and bring the design back into balance. In the example shown in Fig. 4 and discussed in detail shortly, action is needed to address the low ARL & DRL sub-metrics. This might be by exploring design choices that adversely affect the higher scoring metrics. But, because a product can only achieve a MIA of its minimum sub-metric, this counter-intuitive step actually increases the product's overall success. In any deterministic design environment, it is thus possible to model the MIA score of a large set of possible design choices and thereby predict, select, and develop an optimal solution.

Table 2
Scores and calculated values.

No.	{TRL,ORL,ARL,RRL,ORL, SRL,IRL,SML,MRL,CRI}	Max	Min	Interval
1	{3,2,2,1,1,1,3,1,1,9}	9	1	8
2	{4 ,5,2,3,2,3,3,5,2,10}	10	2	8
3	{7 ,14,5,3,3,7,7,7,8,10}	14	3	11
4	{14,14,5,4,6,9,14,10,10,11}	14	4	10

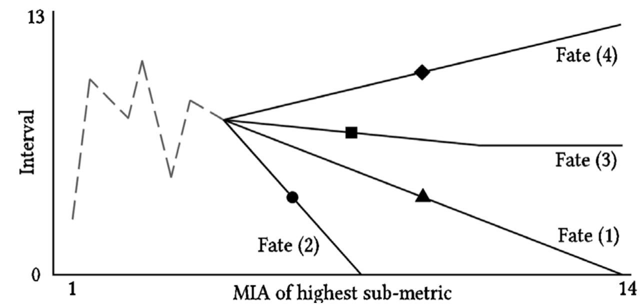

Fig. 2. Interval trends and product fate.

4.2. Interpreting the interval and predicting product fate

With multiple MIA assessments and therefore multiple calculated values for the interval, it is possible to infer trend data of how the design is evolving over time. A graph of the interval vs. the highest sub-metric score shows not only the absolute interval value but also a slope which is of great interest since this derivative indicates whether the design is becoming more or less unbalanced with time. There are several possible interval trends during product development, and these can be used to model the potential fate of the product, as shown in Fig. 2. The fates are found by taking the interval at each assessment point and plotting this against the score of the highest sub-metric. We identified 4 principal fates ranging from (1) best outcome, to (4) worst outcome.

- Fate 1 (triangles): in this ideal fate all the sub-metrics eventually attain MIA scores of 14 and the interval is 0. This best-case scenario describes a maximally successful and balanced design that cannot be further optimised. This is the designer's goal.
- Fate 2 (circles): the trend is for all the sub-metrics to eventually attain high (but <14) MIA scores and the interval is 0 indicating a balanced but non-optimal product (as might be found through a heuristic design approach). In this case the design appears to be heading towards moderate success, but its further improvement may be being limited either by poor design choices or by some constraint that cannot be overcome by further work — e.g., a fundamental law of nature, or a material requirement for elements that do not exist. Regardless, the designer should still attempt to address the underlying issue.

[1] Link available on request.
[2] Link available on request.

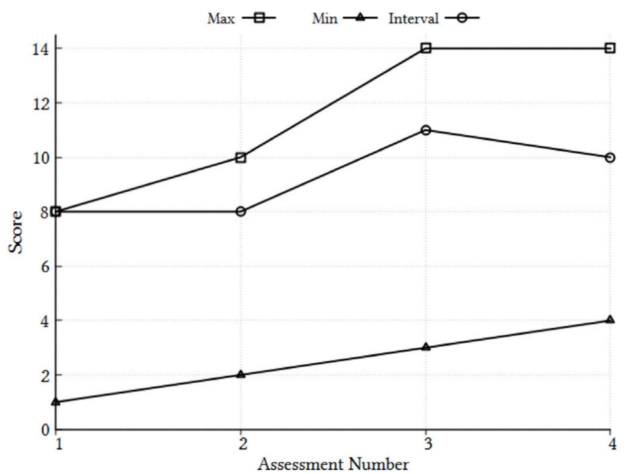

Fig. 3. Plots showing the calculated values (max, min, interval) from Table 2.

- Fate 3 (squares): the interval trend is static and the interval is non-zero. The design is thus unbalanced and the situation is neither improving nor worsening. The designer should consider some more radical change of approach that attempts to lower the interval and improve the product outcome if this will raise its overall MIA. The outcome from the design changes may, if successful, evolve the product into fates (1) or (2), or if neutral the fate remains at 3. It is also possible that the changes produce a negative effect.
- Fate 4 (diamonds): this trend is to be avoided. The interval is increasing and the design becoming more unbalanced. This trend indicates a fundamental problem of design choices that should be immediately addressed. An extreme manifestation of this fate best illustrates why it is to be avoided: in this situation there can be a design that fully satisfies all but one of the sub-metrics, which remains at the lowest score. A product such as this may appear (i.e. by the sub-metric modal value) highly likely to achieve success but our analysis suggests this is a mistaken assumption because success is defined by the minimum sub-metric function, and not on the basis of an average score.

We illustrate the four application cases with examples.

4.3. Case 1 — Single product, single assessment

In this simplest case, an assessment is made of a product with the ten sub-metrics to produce a score for each which can be plotted on a spider diagram (Fig. 4).

The spider diagram shows each metric on a scale of MIA 1 – 15 (diamonds) with the score of MIA 14 for each sub-metric being the target (circles). The feint sector divisions and placements show how the individual sub-metrics align to MIA numbers in accordance with Table 1. This kind of diagram therefore conveniently shows both individual sub-metric scores, and also visually by area, the product's overall holistic MIA situation. In this example the product has attained a MIA score of 4, this being limited by the lowest sub-metric score (ARL and DRL).

4.4. Case 2 — Single product multiple assessments

By making multiple assessments during the development of a product we can infer trend data about its progress. The assessment timing (i.e., when to make the assessments) for the product should be chosen to suit the timeframe of its development.

The product in Fig. 5 has been assessed 4 times during its lifecycle and has made steady progress to high MIA scores in some metrics,

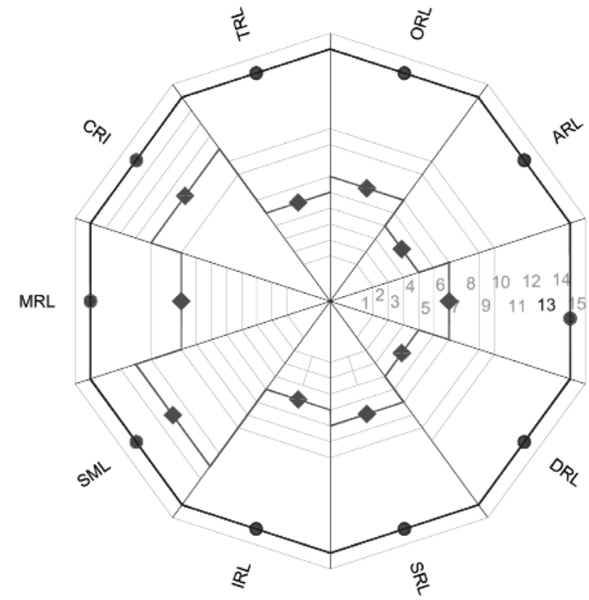

Fig. 4. Hypothetical product scores (diamonds) & ideal MIA 14 scores (circles).

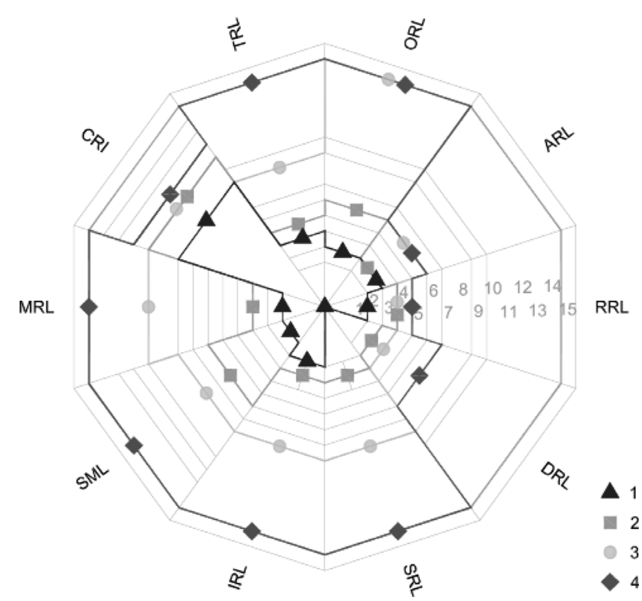

Fig. 5. Multiple assessments showing the evolution of a product during its lifecycle.

(e.g. TRL, ORL, MRL, SML, IRL, SRL). Its progress in CRI is moderate but halted short of its maximum. The progress in sub-metrics ARL, RRL and DRL is poor. ARL, for example, only progressed once between the 4 assessments. Despite high scores in many metrics, this product's highest overall score is MIA 4 since this is the highest score reached by the lowest of the sub-metrics (RRL).

Fig. 3 shows the hypothetical product's calculated values over the 4 assessments. From assessment 1–2 the interval (= 8) remains unchanged since both the min and max sub-metric scores rise equally (fate 3). The interval becomes worse and the design more unbalanced between assessments 2–3 since the maximum rises but the minimum remains unchanged (fate 4) Finally, the interval and design balance improve between 3–4 since the minimum rises and the maximum is at its limit (fate 1 or 2).

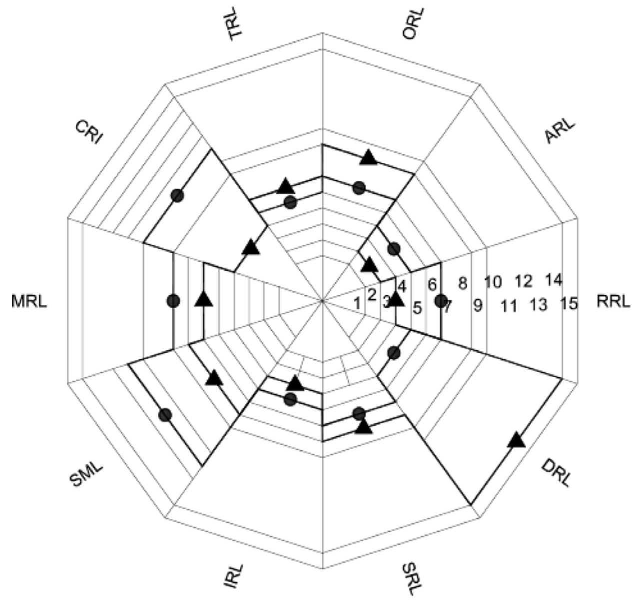

Fig. 6. Comparison of two hypothetical designs. Design 1 (circles), design 2 (triangles).

4.5. Case 3 — Multiple products single assessment

This case is intended to provide differential assessment in any situation where more than one approach is under consideration to solve a design problem such as during technology selection, or the concept selection phase of product design. The analysis proceeds by assessing each design individually as described in case 1, then comparing results. Fig. 6 shows two designs compared and shows that design 1 (circles) is stronger commercially and in sustainment, whereas design 2 is stronger in demand and from organisational readiness. Design 1 has reached MIA 2 (limited by ARL) and design 2 has reached MIA 4 (limited by DRL). From this analysis, the designer has cues to better understand why (qualitatively) a solution has higher or lower sub-metric scores than another, and in what quantity. This analysis can be extended to model the likely outcomes of intervals and fates associated with all the alternative approaches to a design problem thus informing the best choice. It can also guide the process of 'controlled convergence' advocated by Pugh (1991) whereby the strongest elements from several design solutions are combined during design iteration to form a new and stronger solution.

4.6. Case 4 — Multiple products multiple assessments

In the final case we consider how multiple designs can be compared over time. A typical application for this analysis is as a project management tool during product engineering and design where monitoring the evolution of alternative designs is required. This method involves performing the assessment in case 3 multiple times, then performing the analysis suggested in case 2 to each alternative. An example showing two alternatives with 4 simultaneous assessments is shown in Fig. 7. We see this application as particularly useful during technology selection because it is a technology forecasting tool, and may inform the more careful allocation of resources in environments such as technology hubs where the goal is to determine which of a set of alternative solutions to the solving of a novel problem is most likely to succeed.

The example scenario in Fig. 7 contrasts how two hypothetical designs might evolve over time from a similar starting position. Design 1 (dotted lines) shows the characteristics of an unbalanced approach that is failing and has a worsening interval (fate 4) as a long-term trend, although the short-term trend between assessments 3–4 shows improvement. Design 2 (solid lines) demonstrates a much better situation where

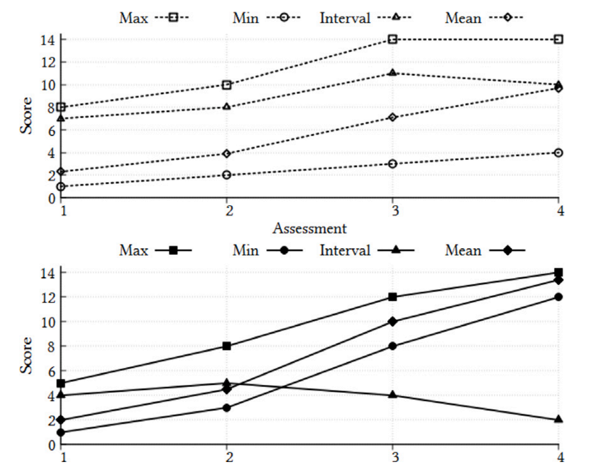

Fig. 7. Two designs compared over time. Design 1 (top), design 2 (bottom).

its interval I shows an improvement ($I \rightarrow 0$) and it is a design that is becoming more balanced (fates 1 or 2 likely). In this scenario, a technology hub for example, would be advised not to pursue design 1 since design 2 is showing greater future potential. In situations where the designer wishes to select the most promising design to pursue, this axiomatic approach determines the optimum choice.

5. Case studies

Application of this technique can uncover flaws within design concepts which then allows for corrective action to be taken. By means of illustrating the methodology we give four brief case studies of products that failed to thrive and give a brief MIA analysis of each failure.

5.1. Betamax

Betamax was a magnetic videotape technology which lost the format war (i.e. market share) with competitor Video Home System (VHS), largely because of deficits in IRL & SRL. Despite having a superior technical product (image & sound quality), Betamax tapes had a maximum recording time initially of 1 h and this was insufficient for the purposes which many consumers were purchasing video cassette recorders (VCRs). Consumers had identified a system configuration to satisfy their need to capture entire broadcasts by integrating the VCR component between the over-the-air signal and the TV set. However, the Betamax product failed this "validation of interrelated functions between integrating components in a relevant end-to-end environment" (Austin and York, 2015) since it did not integrate with existing media durations. One hour was insufficient to capture the typical full length film, for example. Corrective action indicated by the MIA method is to increase the integration component at the expense of the technical component in order to raise the overall MIA score. In most cases involving tape media, this is achieved by slowing the transport speed which trades the signal bandwidth against run time. Betamax only took this step as a revision to the original product (Beta II) and by which time most consumers had already invested in the competition.

5.2. Cuecat

The Cuecat Barcode Scanner was a handheld device connected to a personal computer by cable that was produced circa 2000 to integrate existing print media such as magazines that were expanding into online publishing. It allowed barcodes within printed media to be scanned so that supplemental content could be accessed that was not included in the printed material. Cuecat failed to gather users despite 500,000

units being given away and $185 m of investment capital. The product performed well on all sub-metrics except demand readiness where it failed to achieve DRL 4 "validation of market" (Paun, 2011). Ultimately and despite its good execution, there was no actual demand for the product at that time. In this case the MIA method cannot improve on the result but instead suggests that the product should have been abandoned as a no-go.

5.3. Tablet computer

The Samsung Galaxy Note 7 was a tablet computer released in 2016. The product was initially very successful with record breaking pre-orders in some countries (Triggs, 2016) and it was well received by industry commentators. However, within 2 months of release, Samsung permanently discontinued the product owing to devices spontaneously combusting which was caused by a battery manufacturing defect. This problem remained even after a product recall and the sourcing of components from a different supplier. Such manufacturing quality issues are constrained by three MRL dimensions: "supplier quality Management", "product quality" and "quality management". The product failed to achieve MRL 8 "test and inspection plans complete and validated for production units". or MRL 9 "Quality targets verified" (OSD, 2018). As a result of the defect the product was banned from sale and its air transport was prohibited. Some industry commentators (Weins, 2016) were of the view that the trend towards integrated rather than replaceable batteries compounded the problem. In the Note 7 only this component (within the product's system) needed replacement to resolve the issue but the battery was not a serviceable part. The approach of serviceability (design "for continuous improvement or in reaction to obsolescence") is the target level on the TRL scale (Rosen et al., 1989; Mankins, 1995; ISO, 2013). MIA analysis suggests that the technical performance characteristic of battery capacity was prioritised at the expense of manufacturing quality. A potential remedy is the selection of batteries with a lesser capacity but of greater reliability. Thus the trade-off results in a higher overall MIA score despite a slightly reduced level of performance.

5.4. General motors EV1

The General Motors EV1 was the first purpose built mass production electric vehicle, released in 1996. The car was made available only under a lease agreement and only to residents of California where regulation mandated 2% of car makers' fleets to be emissions-free vehicles and where car makers were required to maintain a service and parts supply for 15 years post-manufacture (sustainment). An analysis of demand indicated that approximately 5000–20,000 cars would be leased per year. In the first year only 288 leases were signed and by the end of production in 1999 only 1117 cars had been produced leading to a failure to progress to DRL 4 ("validation of market confirmed") (Paun, 2011). Leasees were entitled to various tax inducements that in CRI terms formed a subsidy (CRI 12 "still requiring government support") (Australian Government, 2014). However, the low demand and the 15 year sustainment requirement rendered the product uneconomic for such low volumes. Rather than complying with sustainment regulations and thereby achieving an SML of 9 "Product Support Package demonstrated in operational environment" (US, 2019), GM made the decision to reclaim all the vehicles and thereby withdraw the product from the market. In MIA terms the EV1 failed in the multiple sub-metrics of demand, regulation, commercial and sustainment readiness.

In addition to these brief examples, we have also applied MIA analysis to explore the development of Concorde in detail. This will be published as a separate paper (in preparation).

6. Discussion

The most valuable application of the MIA approach is as a proactive design methodology. The key is understanding the characteristics of an unbalanced design and applying this knowledge to improve a product while it is under development. The method allows for both a qualitative and quantitative analysis that is suitable for assessing single or multiple designs either once or many times during their lifecycle and incorporates a strategy to maximise the product's success. Design choices must be made to improve the MIA overall score rather than one single aspect of it. The methodology is particularly suited to products that are currently at a very low MIA score. Products that originate from bottom-up/program push discoveries made in pure research settings where the only sub-metric applied to them (if at all) tends to be TRL measuring the performance of the core functionality. We suggest that this approach to evaluation is insufficient in anything other than the theoretical research environment.

A persistent barrier encountered while attempting to progress from a theoretical research environment is the Valley of Death problem. We offer an MIA perspective on this problem in the next section.

6.1. Insights into the valley of death problem

Crossing the valley of death (VoD) is a well-recognised problem that can occur during product development. It is said to occur "during the initial stages of innovation, at the transition between original scientific research and the commercialisation of associated technologies" (Ellwood et al., 2020) The problem typically manifests when a novel concept requires investment capital to proceed during the 'fuzzy front end' (Lefebvre et al., 2020) (MIA 1 - 11) leading to a division between the two parties of investor and entrepreneur. Investors typically incorporate risk into the investment decision which is known in the economic literature as "trust" (Carpentier and Suret, 2015), a subclass of risk problems where the risk "depends on the performance of another actor" (i.e., the entrepreneur). Trust is especially important in situations where the entrepreneur is unknown to the investor since decisions are often made by word-of-mouth where there is an absence of prior trading history on which to otherwise assess risk. During the fuzzy front-end phase, investors typically face a trust issue stemming from risk in one of three categories — agency (Shane, 2003), market (Erikson et al., 2003), and execution (Carpentier and Suret, 2015). The agency risk, where the entrepreneur may act opportunistically in ways that are not in the investor's interest, typically dominates the trust calculus and is caused by information asymmetry (Chemmanur and Chen, 2014). The VoD problem can be analysed using MIA since we have introduced sub-metrics to describe the product from separate perspectives including commercial factors (CRI).

To make observations on the general case of how a balanced design should progress through the MIA levels, we took the MIA/sub-metric alignment chart shown in Table 3 and applied various functions to the set of sub-metric scores. The results are graphed in Fig. 8.

We observe from the graph that in the general case, a product does not make linear progress on all the sub-metrics simultaneously over its entire lifecycle. The sum trace shows an approximately linear trend until MIA 8. Thereafter until MIA 10 the slope steepens before tapering off at >MIA 10 indicating that some event occurs during the MIA 8 - 9 transition. Similarly, the 1\sum trace indicates, by being composed of two separate curves that intersect at MIA 8, that there are two underlying phases at play. The product trace has an s-curve shape where the inflexion point is present between MIA 8-9 and a similar inflexion point occurs in the product of logs trace in the same location. Finally, the most significant result occurs in the interval trace which displays a linear trend to zero between MIA 1 - 8, then an abrupt discontinuity during the MIA 8 - 9 transition, followed by another linear trend to zero between MIA 9 - 14.

Table 3
General case MIA-adjusted scores with calculated values at each MIA level.

Sub-metric	MIA													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
MIA_{TRL}	1	2	3	4	5	6	8	8	9	14	14	14	14	14
MIA_{CRI}	8	8	8	8	8	8	8	8	10	10	11	12	13	14
MIA_{MRL}	1	2	3	4	5	6	7	8	10	10	14	14	14	14
MIA_{SML}	1	2	3	4	5	6	7	8	10	10	11	12	14	14
MIA_{IRL}	2	2	3	4	5	6	7	8	14	14	14	14	14	14
MIA_{SRL}	2	2	3	4	5	6	7	8	14	14	14	14	14	14
MIA_{DRL}	1	2	3	4	5	6	8	8	9	14	14	14	14	14
MIA_{RRL}	1	2	3	4	5	6	8	8	9	14	14	14	14	14
MIA_{ARL}	1	2	3	4	5	6	8	8	9	14	14	14	14	14
MIA_{ORL}	1	2	3	4	5	6	8	8	9	14	14	14	14	14
Sum	19	26	35	44	53	62	76	80	103	128	134	136	139	140
Min	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Max	8	8	8	8	8	8	8	8	14	14	14	14	14	14
Interval	7	6	5	4	3	2	1	0	5	4	3	2	1	0
Product	3.2×10^{1}	4.10×10^{3}	1.57×10^{5}	2.10×10^{6}	1.56×10^{7}	8.06×10^{7}	6.29×10^{8}	1.07×10^{9}	1.16×10^{10}	1.05×10^{11}	1.79×10^{11}	2.13×10^{11}	2.69×10^{11}	2.89×10^{11}
1/sum	0.05	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Product (log)	0.00	0.00	0.00	0.01	0.04	0.09	0.28	0.36	1.04	2.60	3.23	3.47	3.80	3.91
Mean	1.90	2.60	3.50	4.40	5.30	6.20	7.60	8.00	10.30	12.80	13.40	13.60	13.90	14.00
Mean (CRI)	1.22	2.00	3.00	4.00	5.00	6.00	7.56	8.00	10.33	13.11	13.67	13.78	14.00	14.00

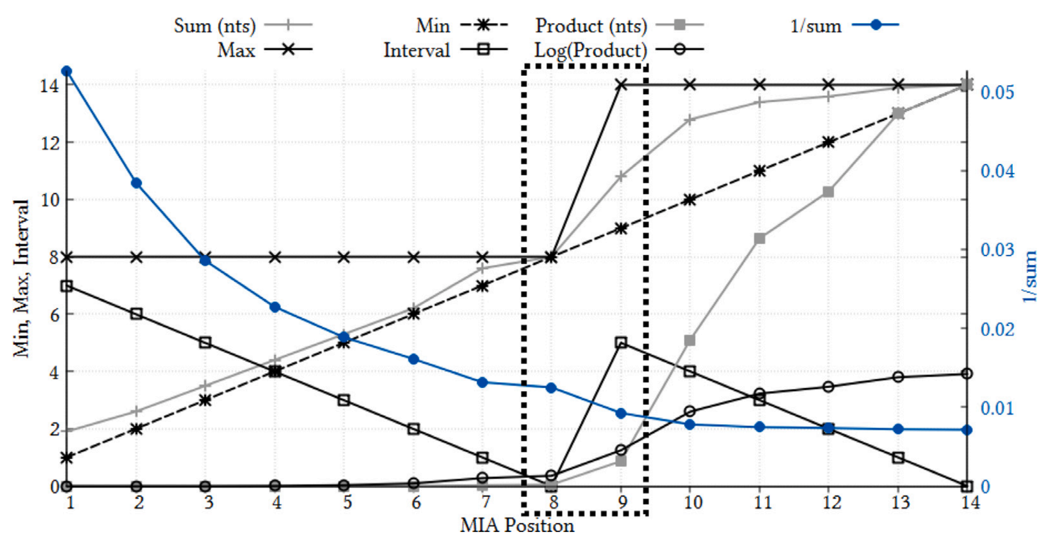

Fig. 8. General case functions of MIA alignment by position. The dotted region highlights where the concatenation of two design phases takes place (see text).

These results are of great interest because the existing design literature posits that the optimum design strategy is where the product is designed holistically (which we quantify by calculating the interval value). Yet, the alignments of the sub-metrics, which should be concordant with this strategy, and which are based on the current readiness literature, appear to indicate that two consecutive half-lives are present, and not one single lifecycle.

By inspection of the alignment in Table 1, the values in Table 3, and the Max trace in Fig. 8, it is evident that while most sub-metrics advance approximately one level per MIA position increase, the CRI sub-metric does not follow this pattern. Its initial value at MIA 1 is CRI 8 and this remains unchanged until MIA 8. Our suspicion is that this outlier behaviour is the cause of the interval discontinuity and the other graphical artefacts in Fig. 8.

To further understand the difference between the CRI progression and the trend of the other sub-metrics, we graphed the CRI sub-metric levels and the mean score of the other sub-metrics (Fig. 9).

The graph, which contrasts CRI progress (squares) vs. the average progress over the other sub-metrics (circles), shows that during the crucial fuzzy front-end (MIA 1-8), the non-CRI mean sub-metric score proceeds linearly (+1/−0) whereas the CRI does not change over this

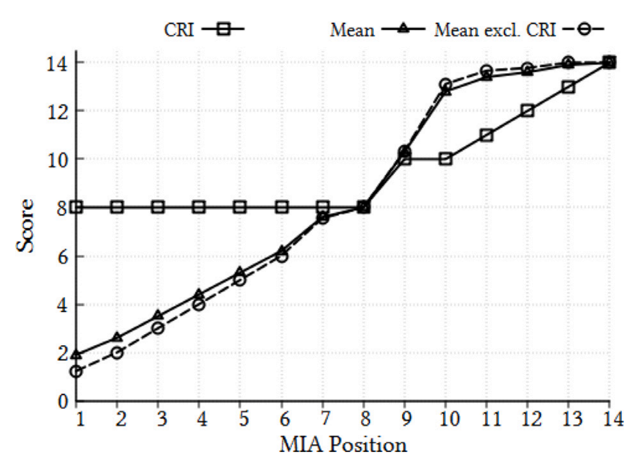

Fig. 9. MIA_{CRI}, mean of the sub-metrics excluding CRI & mean metric scores vs. MIA position (general case).

range. Between MIA 1 - 9 no progress occurs in the CRI sub-metric. Thus, from the commercial perspective the product remains a "hypothetical commercial proposition" that is "commercially untested and unproven" and remains a "proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims." (Millson and Wilemon, 2002). The investor thus faces a situation where no deliverables in terms of the CRI sub-metric are manifested during the bulk of the fuzzy front-end stage and it is into this situation, and with this great uncertainty that the capital must be risked (a "high-risk, low data decision" OSD, 2018). The product can advance in many other sub-metrics, but the commercial status of the project does not change until MIA 9. It is this situation where the entrepreneur has abundant technical knowledge, but the investor has little commercial knowledge that we suppose represents the asymmetry of data that causes the primary risk to be borne by the investor. Put simply, the problem is that the investor cannot measure progress while the capital is at risk and knows that the decision to invest must be made under this complex scenario.

Fig. 9 shows there are two 'phases' bisected by MIA 8. Fig. 8 shows that the interval, which we have previously defined as a measure of the unbalance of a design, does not have a single trend to 0 but instead has two distinct 'phases' that are intrinsic to the MIA sub-metric alignments. The stages are not an artefact generated because of this analysis but are a direct reflection inherent in the product design process as it is currently understood collectively, to work. The interval is derived from the alignment of the sub-metrics which have been suggested by others independently in the literature (especially (Australian Government, 2014)). This analysis shows a representation of why the valley of death problem occurs. During this first phase, which may be called the technical phase, the interval upper bound (max := MIA_{CRI} 8) does not improve while the min values progress. During this phase there is no measurable commercial progress but progress in other sub-metrics with growing information asymmetry. Once this phase is completed and the VoD crossed (assuming the necessary investment), steady progress is then expected with the commercial metric while the remaining other development is quickly completed. This phase may be called the commercialisation phase. We suggest the phase labels with hesitation as we view the discontinuous interval as a methodological problem to be overcome rather than two separate phases into which a design problem should be deliberately decomposed. Our view is that the discontinuity of interval in Fig. 8 is a problem that should be eliminated from product design methodology.

The VoD problem manifests itself as a product that reaches MIA 8 but fails to progress through a commercial phase (failing to cross the VoD) and this type of outcome we have already defined as a fate of 2 (Fig. 2). Consequently, we consider that the VoD problem is actually a special case of an unbalanced design that leads to a fate 2 outcome. The alignment of the sub-metrics reflects the prevailing view in the literature to finish technical activities before commercialisation is seriously considered. We suggest that the VoD problem is a structural problem inherent in current design theory that should be eliminated. This partial analysis problem is exactly what our holistic approach is designed to remedy.

We make the following observations to improve the situation:

(1) We expect that the solution to the VoD problem will involve much closer and more detailed communication between investor and innovator during the fuzzy front end to reduce the information asymmetry. We have endeavoured to produce a method which allows the two parties to better quantify and understand each other's positions.

(2) The commercial aspects of the product should be given an equal weighting to its technical performance. The MIA method provides constant cues of the importance of commercial factors especially at an early point in the product lifecycle.

(3) Increasing the resolution of the CRI sub-metric and/or its design dimensions will yield more discrete levels to be integrated into the MIA method. Increasing the resolution and levels, especially in <MIA 9 positions where the CRI score does not currently change, gives more opportunity for the metric to advance. This allows for improvement to be measured and thus the discontinuity of the interval is reduced in magnitude.

7. Conclusion & Further work

In this work we have proposed a single multi index analysis as a method of assessing a product's development holistically over its entire lifespan. The index contains sub-metrics which assess a product from multiple specific perspectives allowing both a qualitative and quantitative analysis. We optimised the assessment process by deduplication of prior work and by retaining the sub-metrics that act as placeholders for specific stakeholders. We then showed for single products how trend data may be inferred from multiple assessments during product development and how this modelling can inform a design strategy to optimise that product's success. We showed how this process may be used to compare different product solutions to a given problem and how this allows for comparisons between solutions that may inform decision making and resource allocation. We described by analysis of the interval the possible fates that await products when the design becomes unbalanced, and we have suggested a means of predicting & avoiding a negative outcome including crossing the VoD.

7.1. Extensibility of this approach

We believe our approach will have application beyond assessing an individual product's development. It could, for example, assist in technology selection or R&D prioritisation in areas of emerging technologies. For example, in quantum computing, there is, as of yet, no clear winner (or set of winners) in terms of the optimal technology platform to use. We believe our approach will be of utility in helping to critically compare the different technology choices for different quantum technology applications, (which we will explore in future work), and inform work on standardisation in this sector (Goldstein, 2021; Chunnilall et al., 2021; van Deventer et al., 2022; O'Sullivan and Brévignon-Dodin, 2012). One might consider also including other metrics such as standardisation readiness level (ITU-T, 2021). For specific applications, judicious choice of specific readiness levels is needed to maximise the utility of our approach. The choice will depend, to some extent, on intent. For instance, applying our methodology to strategic prioritisation of emerging technology development would have different needs from the tool's use for in-house development of a specific product.

A concrete example is in the area of quantum key distribution (QKD). This is a quantum technology with a very high technology readiness level and there are now a number of commercially available QKD products. While there has been some activity in the area (ETSI, 2023), a key factor preventing their widespread adoption, especially in the banking industry, is a lack of accepted, verified and validated assurance methods and standards. When considering quantum communications for banking applications, one should add to the MIA an assurance readiness level index to assess the maturity of the technology within the system in which it is to be used. We see therefore that in use, each spoke of the MIA spider diagram will represent a separate concern against which readiness for the application at hand can be assessed. The readiness of a technology or application is then indicated by the lowest score of any given scale/concern being considered. This means that choosing the relevant scales for each use-case is crucial to the usefulness of this method, with each scale representing an appropriate separation of concerns. For this reason, an MIA should include only those indices relevant to the use-case at hand while guaranteeing 100% coverage of concerns. Its use should therefore enable the identification of readiness-gaps early in the development process thereby assisting in accelerating technologies to market.

Table 4
Sub-metrics and original design dimensions.

No.	Design dimension	Submetric	
1	Technical proficiency	TRL	Technology Readiness Level
2	Regulatory environment: maturity of the planning, permitting & standards	CRI	Commercial Readiness Index
3	Stakeholder acceptance: maturity of the process for evidencebased stakeholder consultation		
4	Technical performance: availability of discoverable technical performance information		
5	Financial costs: availability of robust, competitive financial information linked to capital and operating costs & forecast revenues allowing investors to take increasing levels of future market & project risk		
6	Financial revenue: availability of robust, competitive financial information linked to capital & operating costs and forecast revenues allowing investors to take increasing levels of future market & project risk		
7	Industry supply chain/skills: the development of competitive & efficient industry product & skills supply chain required to support a commercially viable sector		
8	Market opportunities: development from a hypothetical commercial plan to the demonstration of a viable market (local and/or overseas) via competitive channels to market & sustainable business models		
9	Company maturity: development of the sector to include established companies with strong credit ratings		
10	Industrial base	MRL	Manufacturing Readiness Level
11	Manufacturing technology development		
12	Producibility program		
13	Design maturity		
14	Production cost knowledge (cost modelling)		
15	Cost analysis		
16	Manufacturing investment budget		
17	Maturity		
18	Availability		
19	Supply chain management		
20	Special handling (shelf life, security, hazardous materials, storage environment, etc.)		
21	Modelling & simulation (product & process)		
22	Manufacturing process maturity		
23	Process yields & rates		
24	Quality management		
25	Product quality		
26	Supplier quality management		
27	Manufacturing workforce (engineering & production)		
28	Tooling		
29	Facilities		
30	Manufacturing planning & scheduling		
31	Materials planning		
32	Product supportability	SML	Sustainment Maturity Level
33	Integration among system components	IRL	Integration Readiness Level
34	System as a whole	DRL	System Readiness Level
35	Product demand	DRL	Demand Readiness Level
36	Regulatory status	RRL	Regulatory Readiness Level
37	Public acceptance	ARL	Acceptance Readiness Level
38	Organisation readiness overall	ORL	Organisational Readiness Level

An interesting avenue for future work would be to investigate how well the method we propose here could be integrated with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) as, for example, Aloini et al. (2018) have shown the utility of that approach in technology assessment for decision support. As with other readiness level work, there are a number of limitations to our approach which include: (a) how to address uncertainly in readiness level assessment and assess the impact of such uncertainty in decision making processes; (b) lack of complete and accurate data on which to make assessments; (c) different ontologies used within different domains of the same sector, or between sectors; (d) the subjective nature of metrics (which might be mitigated or at least understood by methods such as TOPSIS).

Regular updates of MIA in spider diagrams such as in Fig. 5 or of analysis as in Fig. 8 would nevertheless help in the accurate evaluation of technologies, designs and design selection.

CRediT authorship contribution statement

David C. Lowe: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Laura Justham:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis. **Mark J. Everitt:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

MJE would like to thank Catherine White (BT) for bringing to his attention issues around the assurance of QKD.

Appendix A

See Table 4.

Appendix B

See Fig. 10.

Dimension		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Technical proficiency	1	X																																						
Integration among technological elements	2		X																																					
Regulatory Environment	3			X																																				
Stakeholder Acceptance	4				X																																			
Technical Performnc Discoverable KPI	5	X				X																																	
Financial Costs	6						X																																	
Financial Revenue	7							X																																
Industry Supply Chain Skills Supply Chain	8								X																															
Market Opportunity	9									X																														
Company Maturity Establ. Companies	10										X																													
Industrial Base	11								X			X																											
Manufacturing Tech. Development	12												X																										
Producibility Program	13													X																									
Design Maturity	14	X													X																								
Production Cost Knowledge Modelling	15						X									X																							
Cost Analysis	16						X										X																						
Manufacturing Investment Budget	17																	X																					
Maturity	18																		X																				
Availability	19																			X																			
Supply Chain Management	20								X												X																		
Special Handling Hazardous Materials	21																					X																	
Modelling & Sim. (Product And Process)	22																						X																
Manufacturing Process Maturity	23																							X															
Process Yields And Rates	24																								X														
Quality Management	25																									X													
Product Quality	26																										X												
Supplier Quality Management	27																											X											
Manufacturing Workforce	28																												X										
Tooling / STE/SIE	29																													X									
Facilities	30																														X								
Manufacturing Planning & Scheduling	31																															X							
Materials Planning	32																																X						
Product Supportability	33																																	X					
Integration Among System Components	34		X																																X				
System As A Whole	35																																			X			
Product demand	36									X																											X		
Regulatory status	37			X																																		X	
Public acceptance	38				X																																		X
Organisation readiness overall	39																																							X

Fig. 10. Design dimension deduplication coincidence matrix.

Appendix C. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.techfore.2024.123559.

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